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Updated Thoracolumbar Injury Assessment Reference Value Guidance for the Upright Seated Male and Female Occupant During Vertical Loading

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14. ABSTRACT

There is a need within the military crashworthiness community to provide occupant protection recommendations to seat designers and program managers to better protect Soldiers involved in rotary-wing mishaps. However, military seat specifications do not require biomechanical response measurements in the test surrogate (Department of Defense [DoD], 1986).The U.S. Army Aeromedical Research Laboratory developed injury assessment reference curves (IARCs) for the Hybrid III 5th percentile female (HIII-5F) anthropometric testing device (ATD) representing small female occupants in vertical impact rotary-wing mishaps. Female post-mortem human subjects were exposed to the vertical accelerative loading conditions required in military specification MIL-S-58095A and match paired to the HIII-5F. The HIII-5F lumbar axial compressive load cell performance IARV was determined for a 10% risk of thoracolumbar spinal injury (AIS 2+). Furthermore, the executive summary of this report provided guidance from previous technical reports to provide IARV recommendations for the 50th and 95th percentile males.

15. SUBJECT TERMS
lumbar spine, vertical accelerative testing, lumbar injury, vertical loading, injury assessment reference values, IARV, female, male

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Executive Summary

There is a need within the military crashworthiness community to provide occupant protection recommendations to seat designers and program managers to better protect Soldiers involved in rotary-wing mishaps. Currently, military seat specifications do not require biomechanical response measurements of an anthropomorphic test device (ATD), commonly referred to as 'crash test dummies' in the automotive industry (Department of Defense [DoD], 1986). The guidance set forth in this executive summary is based on the culmination of vertical acceleration work completed by the U.S. Army Aeromedical Research Laboratory (USAARL) to assess thoracolumbar spine injury risk for the seated occupant in rotary-wing mishaps.

The USAARL conducted four studies to assess thoracolumbar injury using the vertical acceleration pulses in military seat specification MIL-S-58095A (DoD, 1986). The first study developed lumbar compressive injury assessment reference values (IARVs) for two ATDs representing the male 50th percentile population: the Hybrid III (HIII-50M) and the Federal Aviation Administration (FAA) Hybrid III (FAA-HIII 50M). The second and third studies leveraged the legacy male post-mortem human subject (PMHS) data from the first study to develop interim IARVs for the Hybrid III 5th percentile female (HIII-5F) and interim IARVs for the HIII 95th percentile male (HIII-95M-PED), respectively (Lafferty et al., 2021; Schlick et al., 2025). The final study, as detailed in this technical report, investigated the spinal injury tolerance of the female population by subjecting whole-body female PMHS to operationally relevant loading conditions. The exposure levels of injury from the legacy male data were used to update interim HIII-5F thoracolumbar IARVs for female aircrew. These newly defined criteria supersede the interim female IARVs and advance the performance standards for crashworthy seating systems by recommending female-specific performance limits. IARVs for a 10% risk of moderate or higher severity thoracolumbar spinal injury (AIS 2+) were recommended for male and female occupants (Table 1).

Table 1. Recommended Lumbar Compressive IARV Guidance for ATDs of Different Soldier Populations Exposed to Vertical Impact Loads

Soldier Percentile / Sex	ATD	Recommended Lumbar Compressive IARV	USAARL Technical Report Number
5th Female	HIII-5F	894 pounds (lb)	Current report
50th Male	HIII-50M	1135 lb	USAARL-TECH-FR--2020-051
50th Male	FAA-HIII-50M	1223 lb	USAARL-TECH-FR--2020-051
95th Male	HIII-95M-PED	1167 lb	USAARL-TECH-FR--2026-04

Based on the results of these studies, the vertical dynamic performance requirements of MIL-S-58095A for rotary-wing seats do not sufficiently mitigate the risk of thoracolumbar spinal injuries. During these studies, male and female PMHS specimens experienced AIS 2+ spinal injuries when exposed to the seat performance thresholds defined in MIL-S-58095A (DoD, 1986). Increased energy absorption will provide additional thoracolumbar spinal injury protection for occupants involved in survivable crashes. Military crashworthy seating specifications need to be updated. Seat designers and program managers should include injury assessments for all Soldier populations in seat performance requirements.

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Introduction

Although the U.S. military population remains largely male, the proportion of females within the military has been increasing and their duty restrictions have been removed. Women served in aviation roles during World War II; however, they were not officially permitted to fly combat missions until 1993 (Office of the Secretary of Defense Public Affairs, 2009). According to the Department of Defense report entitled "2022 Demographics: Profile of the Military Community," 15.7% of enlisted personnel were female in 2022, up from 11% in 1990 (Department of Defense [DoD], 2022). As the female Soldier population grows and females occupy more combat positions previously performed solely by males, the standards and injury criteria for protective gear and equipment must be revised to accommodate possible differences in injury tolerances due to injury tolerance and anatomical differences between sexes. Anatomical differences between the male and female pelvis and lumbar spine, such as sacrum angle, vertebral geometry, and lumbar lordosis could alter the loading path through the body and influence injury tolerance. Currently, no military crashworthy seat standard provides anthropomorphic test device (ATD) performance requirements to assess male and female occupant injury risk during injurious vertical accelerative loading events. Guides such as the Joint Service Specification Guide Crew Systems Crash Protection Handbook (JSSG-2010-7) offer guidance, but it not a requirement document (DoD, 1998).

The development of aircraft crashworthy design standards and guidelines culminated in the 1970s and 1980s, with the publication of the U.S. Army Aircraft Crash Survival Design Guide (ACSDG) and subsequent revisions. Identification of injury risks and hazards depended heavily on the U.S. Army aviation crash experience during the Vietnam conflict. These crashworthy guidelines encompass all elements of aircraft design, including structural design, retention of high mass items, fuel systems, energy attenuation, occupant restraint, emergency egress, cockpit delethalization, and post-crash hazards. The seating systems are critical to occupant injury mitigation as they provide vertical energy attenuation to reduce spinal injury risk during vertical impact events and include occupant restraint systems to reduce occupant flail by providing occupant retention. Two military specifications for rotorcraft seating systems that resulted from the crashworthy guidelines are MIL-S-58095A (for cockpit seats) (DoD, 1986) and MIL-S-85510 (for cabin seats) (DoD, 1981). However, MIL-S-58095A (DoD, 1986) was canceled in 1996 (DoD, 1996a). Later that year, the U.S. Navy specification for crashworthy helicopter cabin seats, MIL-S-85510 (DoD, 1981), was deemed inactive for new designs and was only used for replacement purposes (DoD, 1996b). One key Military Standard, MIL-STD-1290A, titled "Light Fixed and Rotary-Wing Aircraft Crash Resistance," was canceled in 1995, but then reinstated in 2006 and validated for acquisition purposes in 2019 (DoD, 1995; DoD, 2019); however, MIL-STD-1290A cites both MIL-S-58095A and MIL-S-85510 for crew and passenger seats. The U.S. Army female population is not included in these specifications. Additionally, MIL-S-58095A and MIL-S-85510 do not assess injury risk and only stipulate seat pan acceleration response thresholds in their dynamic requirements.

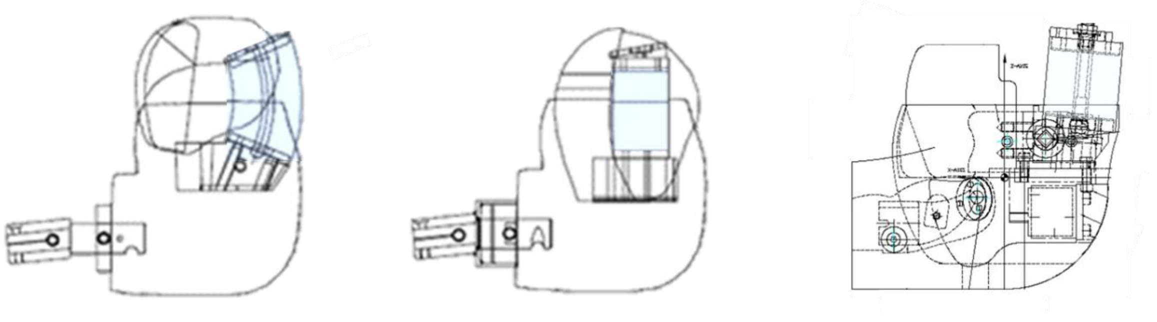
In response, seat designers and program managers have been working to develop more protective seats but, unfortunately, are doing so without updated performance criteria. Most current U.S. Army aviator seats were designed to the specifications of MIL-S-58095A, requiring measurement of seat stroke distance and seat pan accelerations, but not direct measurement of the lumbar forces and moments in test surrogates (DoD, 1986). The measurements in this standard have not been correlated with biomechanical responses in humans. The seat pan acceleration metric used in these legacy performance specifications was established because, at the time, the instrumentation available for ATD integration was not mature enough to produce reliable measurements, and validated injury assessment metrics were not available for the thoracolumbar region of the spine.

To assess injury risk from exposure to dynamic environments, ATD injury assessment reference values (IARVs) are required and need to be developed for dynamic conditions (i.e., accelerative direction, peak acceleration levels, velocity change, etc.) with appropriate ATD size representation, instrumentation, and biofidelity. IARVs are developed through matched-pair testing that subject identical test conditions to PMHS and different ATD designs. By comparing PMHS injury response data to ATD sensor response data collected from the same dynamic conditions, the injury risk can be correlated with the ATD sensor response data. Injury correlations are then made from the matched-pair testing specific to exposure, body region, and ATD used (Rhodes, Flath, et al., 2022) to develop injury assessment reference curves (IARCs). The specific injury limits for a selected injury risk, used to test vehicle materiel and equipment performance, are known as IARVs. Rhodes, Flath, et al. (2022) and Rhodes, Willett, et al. (2022) noted IARVs that are appropriate for military exposures; however, there is a notable lack of IARVs specific to the female Soldier in the thoracolumbar region. Female Soldiers are expected to have a lower injury threshold than their male counterparts during vertical accelerative loadings due to anatomical and anthropometric differences; therefore, biomechanical performance and injury risk for the military relevant dynamic loading conditions need to be quantified to be incorporated into updated crashworthy seat standards.

The U.S. Army Aeromedical Research Laboratory (USAARL) has studied the relationship between seat pan acceleration versus ATD instrumented pelvis and lumbar segment responses, and the risk of thoracolumbar injury with male PMHS subjected to vertical accelerations (Lafferty et al., 2020). This prior study exposed whole-body male PMHS and ATDs to survivable impact accelerations representative of the seat performance levels specified in MIL-S-58095A (Lafferty et al., 2020). PMHS injuries were quantified according to the abbreviated injury scale (AIS) (Generalli & Wodzin, 2006). Matched-pair tests were conducted with both the standard automotive 50th percentile male Hybrid III (HIII-50M) and the Federal Aviation Administration modified Hybrid III (FAA-HIII 50M) ATDs (Humanetics Innovative Solutions, Farmington, MI). Results of the matched-pair testing were used to develop IARCs relating the lumbar spine compressive axial loads measured in the mid-size male ATDs to the AIS coded injuries identified in the PMHS post-exposure (Lafferty et al., 2020). Different IARVs for the HIII-50M and FAA-HIII 50M were developed and recommended from their respective IARCs for a 10% risk of AIS 2 or greater (AIS 2+) thoracolumbar injury.

Additionally, an interim scaled IARV was developed for the Hybrid III 5th percentile female ATD lumbar load cell from the legacy male PMHS data (Lafferty et al., 2021). Two approaches were used to develop this interim IARV. First, a basic mass scaling approach was applied, which resulted in a lumbar compressive load IARV of 760 pounds (lb). A second experimental approach consisted of performing matched tests with the Hybrid III 5th percentile female (HIII-5F) ATD against the prior male PMHS tests. The resulting IARVs were scaled by 85% to adjust for known vertebral body strength differences between males and females (Ebbesen et al., 1999; Mosekilde & Mosekilde, 1990). This more robust experimental-computational approach resulted in a lumbar load IARV of 909 lb. Lafferty et al. (2021) recommended a lumbar compressive load IARV of 909 lb for the HIII-5F.

The HIII-5F lumbar spine design differs from the spine of the H-III males (Figure 1). The HIII-5F has a straight spine to represent an erect driving posture. The FAA-HIII also has a straight spine although the spine is configured at a different angle than the HIII-5F. Differences in ATD construction and body weight must be considered during the development of IARVs. Each IARV developed is specific to the ATD and the exposure being evaluated.



HIII-50M **FAA-HIII** **HIII-5F**

Figure 1. Illustrations of the HIII-50M, FAA-HIII, and HIII-5F lumbar and pelvis segments. Figure adapted from Gowdy et al. (1999) and Humanetics (2020).

The current study, conducted with female PMHS, sought to either validate the interim recommendation or provide critical data needed to revise it. Building upon the developed IARCs and research methodology of Lafferty et al. (2020), this work further develops a lumbar spine compressive load injury risk assessment capability for the female population. This research is crucial to updating aircraft crashworthy seat standards such as MIL-S-58095 and MIL-S-85510 (DoD, 1981; DoD, 1986) by correlating ATD biomechanical metrics with bony damage in humans, especially among females. The resulting female lumbar compressive load IARVs could be incorporated into existing or future crashworthy seat standards to ensure performance levels minimize the thoracolumbar injury risk and accommodates the expanding anthropometric range of Service Members.

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Methods

PMHS Selection and Instrumentation

This study complied with the U.S. Army Cadaver Policy (DoD, 2020) and was approved by the U.S. Army Medical Research and Materiel Command (now the U.S. Army Medical Research and Development Command) Office of Research Protections (USAMRDC ORP). For inclusion in this study, all specimens were initially screened based on the following criteria:

- Females between 17 and 80 years of age;
- Free of traumatic damage, radiographic anomalies (including fractures), signs of osteoporosis or osteoarthritis, or cancer that has metastasized in the bone;
- Without existing, unhealed soft tissue injury;
- No evidence of wasting disease;
- Serology exams ensured no history of HIV, hepatitis B or C, COVID, or syphilis; and
- Specimens did not undergo any embalming process.

Four female PMHS were instrumented with six degree-of-freedom (6DOF) sensors (3 linear accelerometers and 3 angular rate sensors) (Endevco [Model 7264C], Halifax, NC and Diversified Technical Services [Pro-8K], Seal Beach, CA, respectively) on the skull, the first and eleventh thoracic vertebrae (T1 and T11), the second or third lumbar vertebra (L2/L3), and the sacrum. The sternum and pubic rami were instrumented with 3DOF linear accelerometers (Endevco [Model 7264C], Halifax, NC). Uniaxial strain gauges (M-Line, Micro-Measurements®, Raleigh, NC) were placed at T1, T11, and L2 (or L3), and three-axis rosette strain gauges were placed on the sacrum and the anterior-superior aspect of the left and right iliac crests. An acoustic sensor (Pico, Physical Acoustics, Princeton Junction, NJ) was mounted to T10 (Figure 2).

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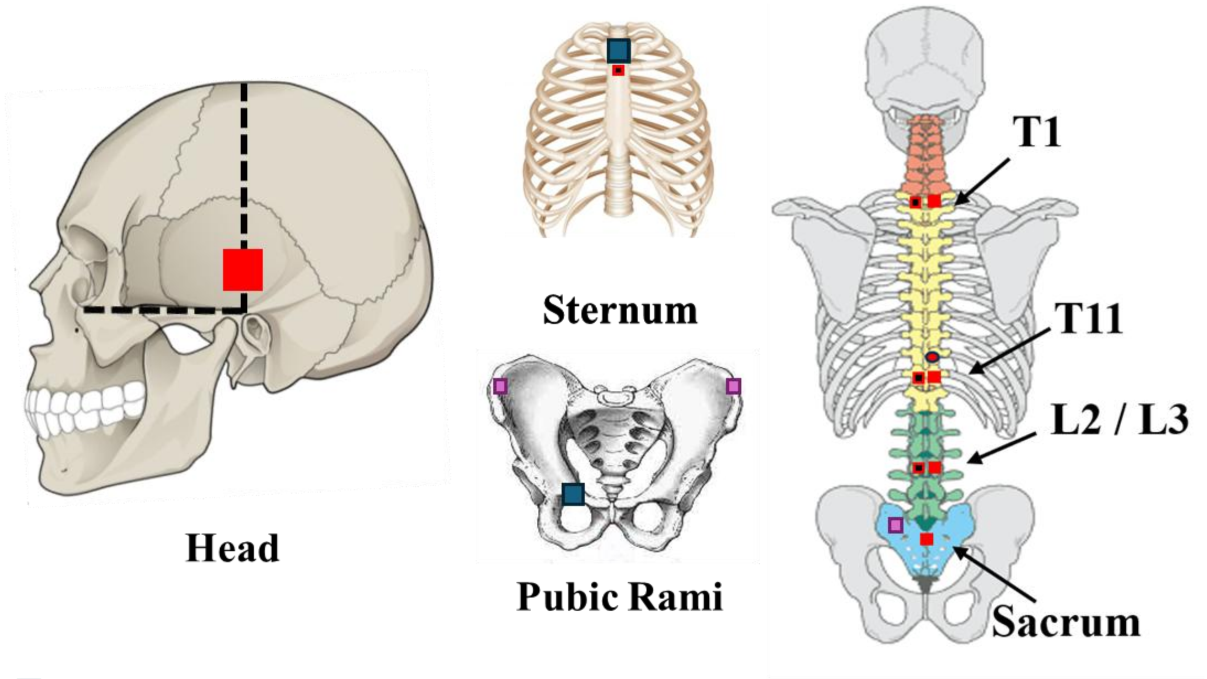

🟦 Sensor mount with three-DOF accelerometer
🟥 Sensor mount with six-DOF sensors (3 accelerometers and 3 angular rate sensors)
▪ Uniaxial strain gauge
🟪 Three-axis rosette strain gauge
● Acoustic sensor

Figure 2. The female PMHS were instrumented with a 3DOF sensor on the sternum and pubic rami, 6DOF sensor on the skull, T1, T11, L2 (or L3) and sacrum, uniaxial strain gauges on T1, T11, and L2 (or L3), a 3-axis rosette on the sacrum and the anterior-superior aspect of the left and right iliac crests, and an acoustic sensor at T10.

All PMHS received medical imaging (computed tomography [CT]; Toshiba Aquilion 64) upon delivery to verify the absence of pre-existing skeletal damage or injury throughout the entire body, especially the pelvis and the spine regions). This imaging also served to document the specimen’s pre-test spinal conditions and geometry.

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Test Setup

The USAARL vertical acceleration tower (VAT) is 40 feet (ft) tall and uses a HyGE (Kittanning, PA) pneumatically-driven firing ram to generate vertical acceleration of a carriage in excess of 75 G (where G is the standard acceleration due to earth gravity [32.174 ft/sec^2) (Figure 3). System input variables, including pressure settings, volumes, metering pin shape, and carriage mass control the acceleration exposure.

Figure 3. The VAT, located at USAARL, is used to apply vertical accelerative crash impulses to seating and litter systems.

A rigid seat was attached to the VAT carriage with a horizontal seat pan and vertical seat back. The rigid seat eliminated the variability from seat cushions or padding. Industry-standard techniques were used to maintain initial PMHS head positioning, with a level Frankfurt plane, while allowing free movement of the specimen during exposure. A five-point restraint system, without a shoulder harness inertial reel, was installed and anchored to the rigid seat and used to secure the PMHS or ATD to the seat and to establish the pre-test position. This restraint system has a rotary buckle assembly positioned at the lower abdomen level that is used to secure the end fittings. The restraint straps were adjusted pre-test to provide 15 to 20 lb and 10 to 20 lb of force in each strap for the PMHS or ATD, respectively. The arms and legs of the test specimen were loosely tethered to allow an unimpeded motion during loading while reducing reactionary extremity flail during carriage deceleration.

All PMHS, ATD, and carriage-related sensor data were collected at 200,000 samples per second. High-speed video images were recorded at 5000 frames per second. Data acquisition and reduction followed the Society of Automotive Engineers (SAE) Recommended Practice J211-1 Part 1 (Society of Automotive Engineers, 2007).

PMHS Testing

The PMHS were positioned in the test fixture seat with target hip, knee, and ankle angles each of 90 degrees (90-90-90; Figure 4), representative of conventional seating. During the positioning process, a coordinate measuring machine, FARO Arm Platinum (FARO, Lake Mary, FL), was used to check and document the posture of the PMHS positioning. Three angles were used to control positioning: the back, hip, and thigh angles (Figure 4). The hip angle was measured as the angle between the shoulder and thigh about the hip and targeted to be 90 degrees. The back angle was measured as the angle between the shoulder to hip segment relative to the vertical seat back and targeted to be less than 2 degrees. The thigh angle was measured as the angle between the knee to hip segment relative to the horizontal seat pan and was also targeted to be less than 2 degrees.

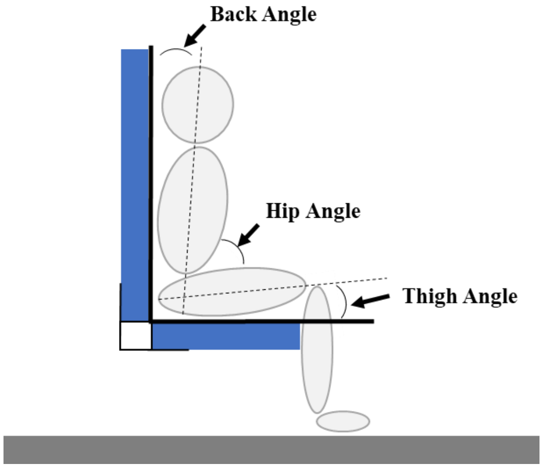

Figure 4. Back, hip, and thigh angles (targeted to 90-90-90) were documented with the FARO arm to ensure matched positioning of the ATD to the PMHS.

The four female PMHS specimens were subjected to the vertical exposures outlined in Table 2. Initially, the 23 G acceleration testing requirement stipulated in MIL-S-58095A and MIL-S-85510 was targeted for the first PMHS. Then, the peak acceleration target levels were lowered, but the target velocity change was held constant, for the last three PMHS to determine if the injury occurred at a lower acceleration threshold. Post-test CTs of the PMHS were obtained to identify and confirm the presence of injury in the spine and incidental injuries in other anatomical regions. Following imaging, instrumentation was removed, and a post-test autopsy was conducted to document injuries and injury severities. A medical examiner (ME) was provided by the Armed Forces Medical Examiner System (AFMES) to conduct the autopsies.

Table 2. Target Exposure Parameters

Specimen	Exposure	Maximum Acceleration (G)	Total Change in Velocity (ft/s)
PMHS 1	1	23	42
PMHS 2	2	16.5	42
PMHS 3	2	16.5	42
PMHS 4	3	14.5	42

Matched-Pair Testing

For each PMHS test, a singular HIII-5F ATD test was conducted as a matched-pair. Matched-pair testing was conducted with the instrumented HIII-5F ATD (Humanetics Innovative Solutions, Farmington, MI). The ATD matched-pair tests were designed to duplicate the PMHS exposure conditions including posture, maximum acceleration, total change in velocity, and onset rate. The four matching ATD tests were conducted by placing the ATD in a posture that matched the PMHS. The ATD was positioned in the seat with the mid-sagittal plane aligned with the center of the seat (Figure 5). During the positioning process, the FARO Arm was used to check and document the ATD posture to match the PMHS test, with particular attention to the back angle.

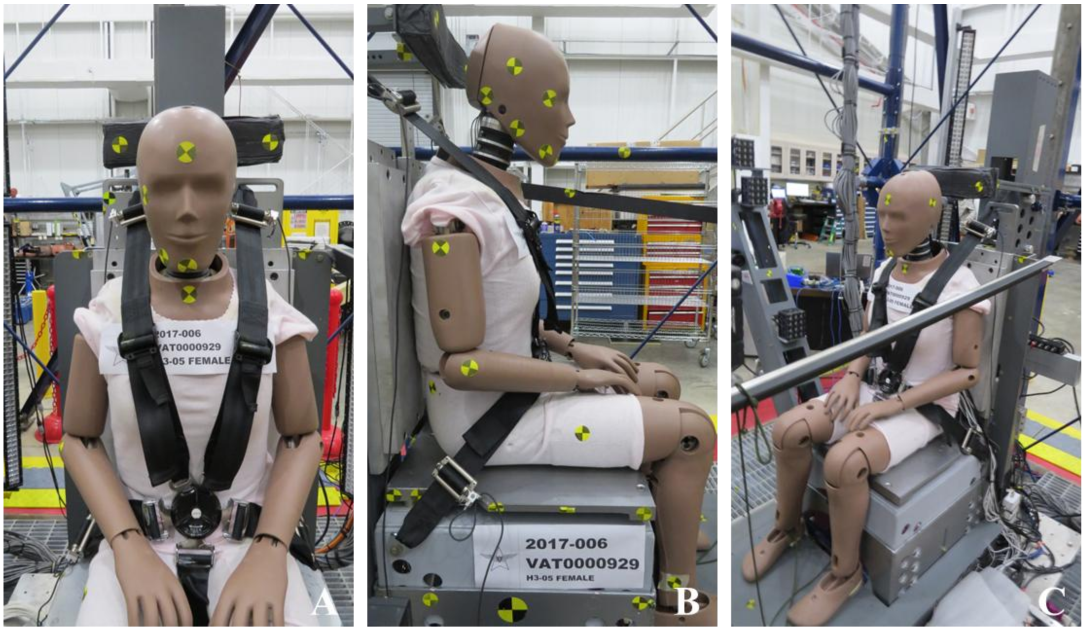

Figure 5. The front (A), side (B), and oblique (C) views of the HIII-5F ATD positioned in the USAARL VAT rigid seat are shown.

Data Analysis

Data were time-aligned based on initial carriage motion as captured by the carriage accelerometer, where time-zero was calculated to be when acceleration, filtered at SAE J211 channel frequency class (CFC) 60, first reached 5% of its peak. Calculated metrics included the carriage velocity and the onset rate from the carriage acceleration. The onset rate was calculated as the maximum onset slope over 5 milliseconds (ms) of acceleration before its peak. The velocity was calculated as the numerical integration of the acceleration-time data.

Fractures were documented photographically, with injury type and severity graded in accordance with the AIS (Generalli & Wodzin, 2006). The PMHS data provided female-specific injury outcomes for the exposure, and the ATD provided the measured responses in different ATD body regions. The HIII-5F axial compressive signals were filtered at CFC 1000 and the peak forces were tabulated.

The IARC was developed using parametric survival analysis techniques pairing the peak axial compressive HIII-5F lumbar load data with the female PMHS AIS 2+ thoracolumbar injuries documented. The best distribution for the IARC was selected using the Akaike information criterion (AIC). The AIC estimated the quality of the survival analysis model given three underlying distributions: log-normal, log-logistic, and Weibull, where the lowest AIC score indicated the best distribution. While injury tests were treated as uncensored, the non-injury tests were treated as right censored (Turkson et al., 2021). The quality of the IARC was checked with the normalized confidence injury score (NCIS) and calculated as the ratio of the IARC confidence interval to the mean value at discrete probabilities. The NCIS values less than 0.5 were considered “good” (Petitjean et al., 2015). Age and bone mineral density were tested as covariates to determine if they influenced the IARC. The IARV was identified at the recommended risk of injury from the IARC.

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Results

Specimen demographics are listed in Table 3. The post-test autopsies revealed thoracolumbar injuries in three out of the four specimens tested (Table 4). All three specimens with a thoracolumbar spine injury sustained a burst fracture categorized as an AIS 3 (serious) injury. Specimen 2 sustained the most severe injury (AIS 4) with a sacral fracture combined with sacroiliac (SI) joint dislocation (Figure 6). The fourth specimen did not sustain a thoracolumbar injury and was associated with the lowest maximum acceleration exposure.

Table 3. Demographics

Specimen	**Age (years)**	**Weight (lb)**	**Height (inches)**	**Bone Mineral Density (mg/cm^3)**	**Cause of Death**
PMHS 1	77	109	60	68.2	Cerebrovascular accident
PMHS 2	69	100	60	77.1	Malignant neoplasm of the cervix
PMHS 3	68	140	62	69.3	Lewy body dementia
PMHS 4	65	195	64	182.3	Metastatic small cell carcinoma
Average St. Dev.	69.8 ± 5.1	136.0 ± 42.9	61.5 ± 1.9	99.2 ± 55.5	

Table 4. PMHS Thoracolumbar Injury Outcomes

Exposure	**PMHS ID**	**Injuries**	**AIS**
1	1	Burst fracture (first lumbar vertebra [L1])	3
2	2	Burst fracture (fifth lumbar vertebra [L5])	3
		Laminar fracture (sixth thoracic vertebra [T6])	2
		Sacral fracture and SI joint dislocation	4
	3	Burst fracture (third lumbar vertebra [L3])	3
		Laminar fracture (first thoracic vertebra [T1])	2
		Vertebral body fracture (second thoracic vertebra [T2])	2
3	4	No thoracolumbar injuries	N/A

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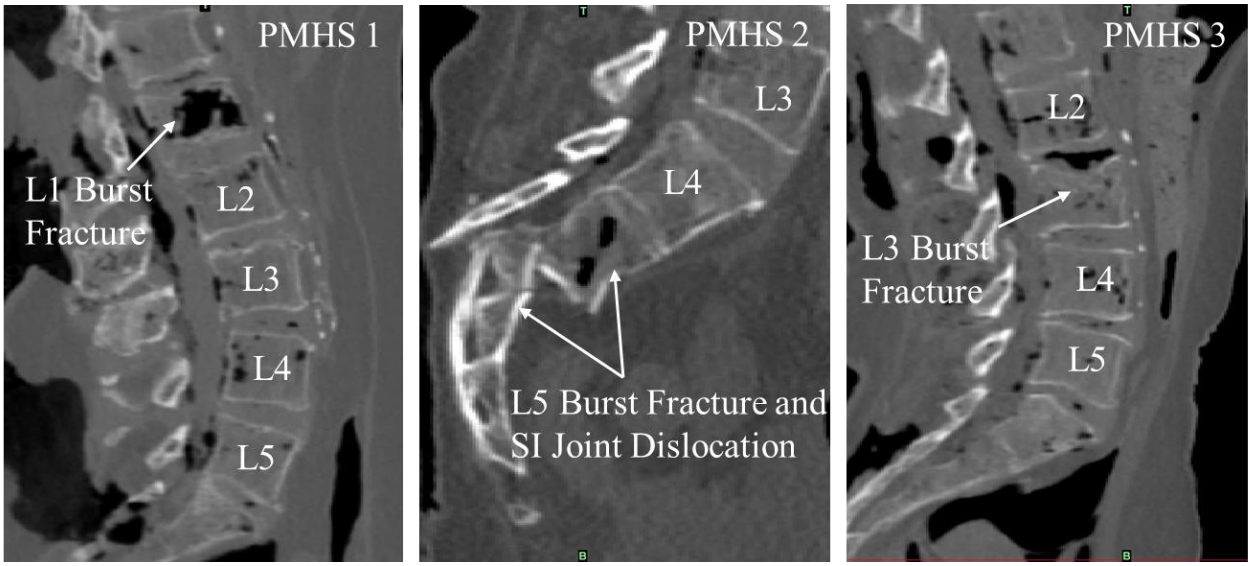

Figure 6. Burst fractures in PMHS 1, 2, and 3 were confirmed initially with CT scans.

Parameters of each PMHS test and its singular HIII-5F ATD test are tabulated below (Table 5) with calculated percent difference (% Diff). Time traces for the matched test carriage accelerations of the PMHS and the HIII-5F for each exposure are illustrated in Figure 7 through Figure 9. All peak carriage accelerations occurred between 0.01 and 0.055 seconds.

Table 5. Exposure Parameters for PMHS and Corresponding HIII-5F Test

Exposure	**Surrogate**	**ID**	**Peak Carriage Acceleration**		**Carriage ΔV**		**Peak Carriage Onset Rate**		**Back Angle**	
			(G)	**% Diff**	**(fps)**	**% Diff**	**(G/s)**	**% Diff**	**(deg)**	**Difference (deg)**
1	PMHS	1	22.0	3.2%	42.4	0.5%	1864.1	-0.6%	-1.1	0.2
	ATD	1048	22.7		42.6		1853.2		-0.9	
2	PMHS	2	16.8	-1.2%	41.7	-1.4%	1152.2	-4.8%	-1.2	-0.3
	ATD	1056	16.6		41.1		1097		-1.5	
	PMHS	3	16.6	-2.4%	41.5	0.2%	1081.1	-0.3%	-1.4	0.7
	ATD	1064	16.2		41.6		1078.1		-0.7	
3	PMHS	4	14.5	0.0%	40.6	2.7%	1065.4	1.7%	-1.0	-0.1
	ATD	1233	14.5		41.7		1083.4		-1.1	

Note. PMHS and ATD tests are grouped by matched-pairs denoted by the shaded and unshaded regions.

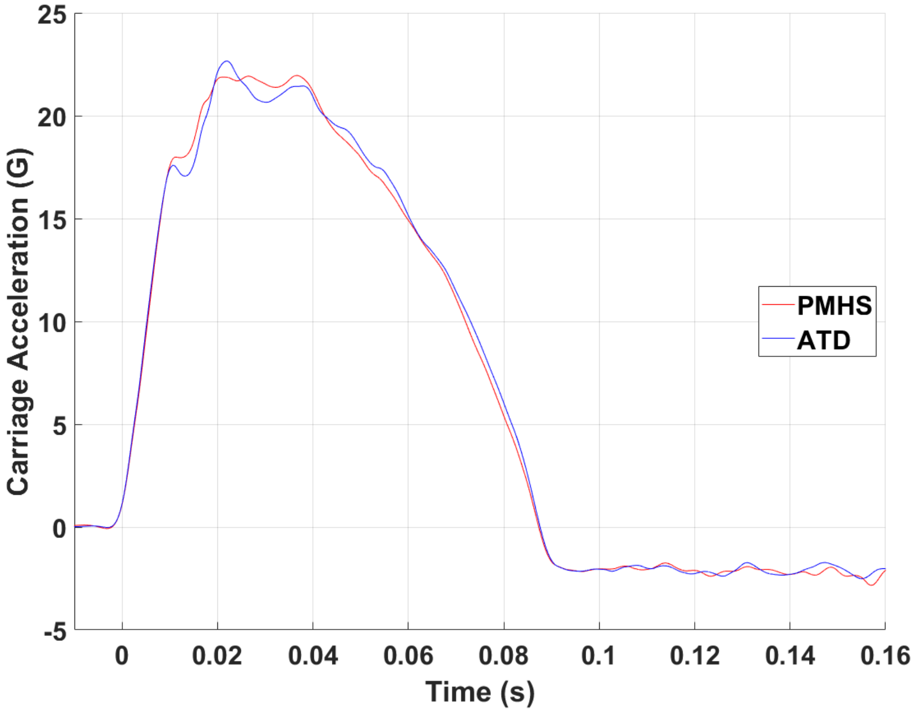

Figure 7. The carriage accelerations of Exposure 1 are shown for PMHS 1 and ATD Test 1048.

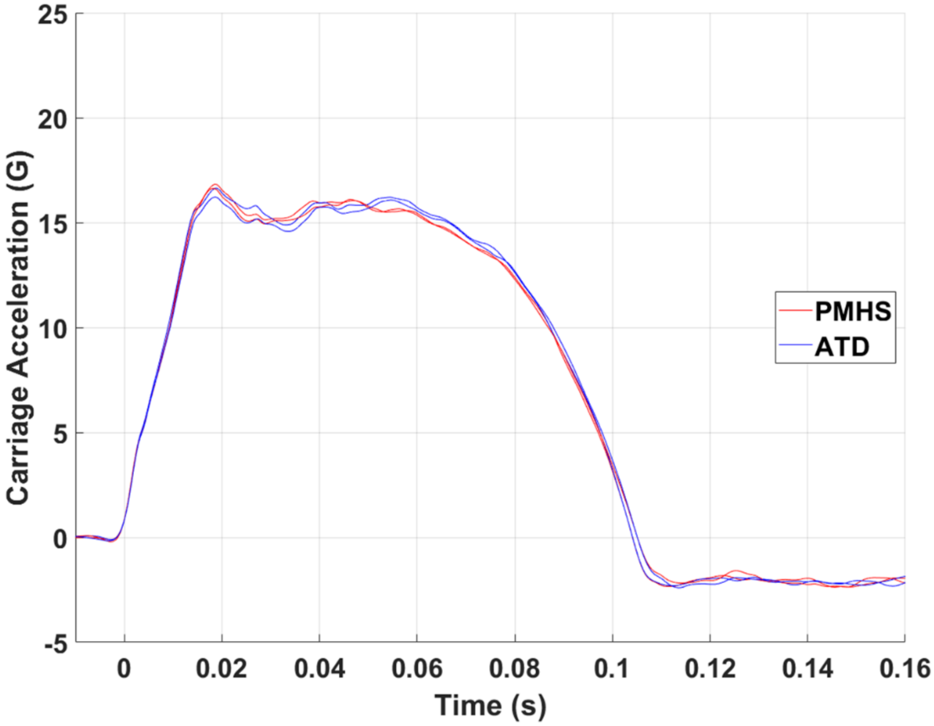

Figure 8. The carriage accelerations of Exposure 2 are shown for PMHS 2 and 3 and ATD Test 1056 and 1064.

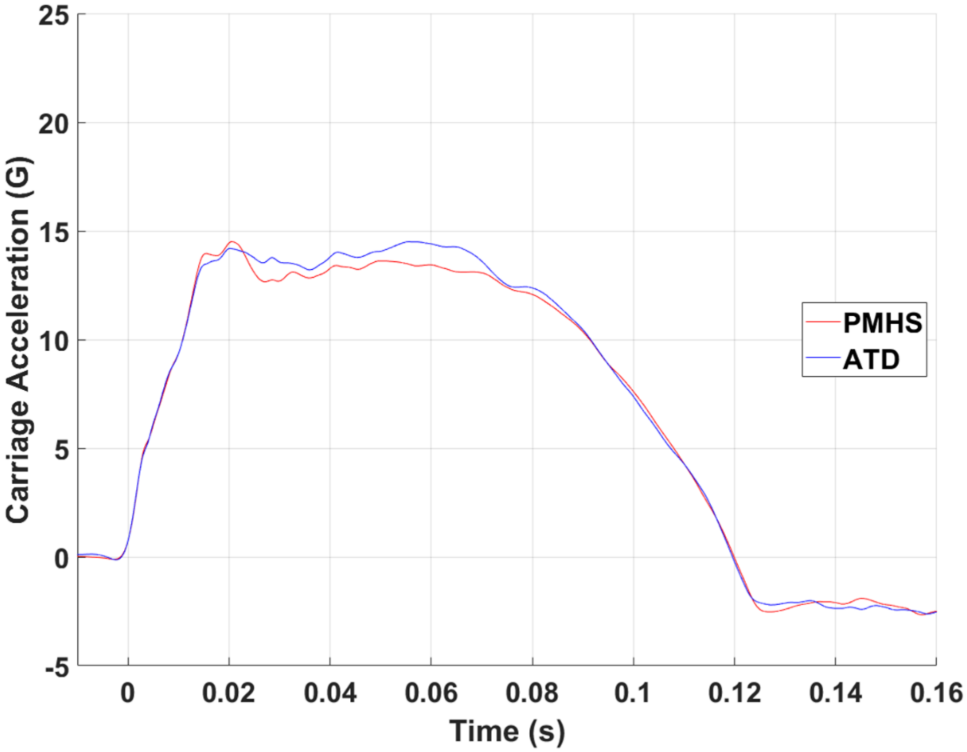

Figure 9. The carriage accelerations of Exposure 3 are shown for PMHS 4 and ATD Test 1233.

The lumbar axial compressive load data collected for each ATD matched-pair test are illustrated and grouped by exposure in Figure 10 through Figure 12. Overall, peak lumbar axial force, the minimum value observed, ranged between -770 and -1403 lb, where negative values are compressive forces (Table 6). Peak loads occurred between 0.02 and 0.04 s of the carriage onset for all exposures.

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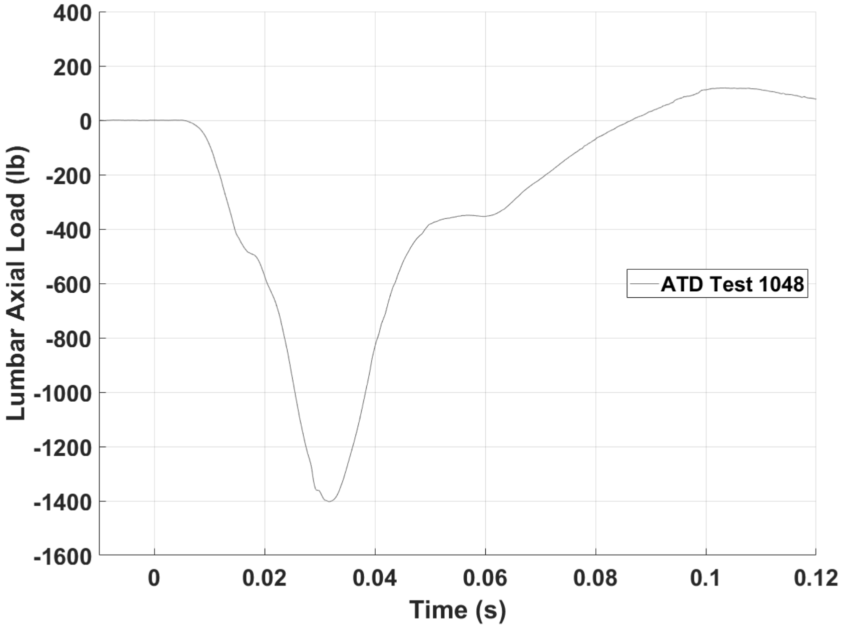

Figure 10. The lumbar axial force versus time data recorded for the matched-pair run at Exposure 1 for the HIII-5F (ATD Test 1048) is shown. The positive axial load values represent lumbar tension and negative values represent lumbar compression.

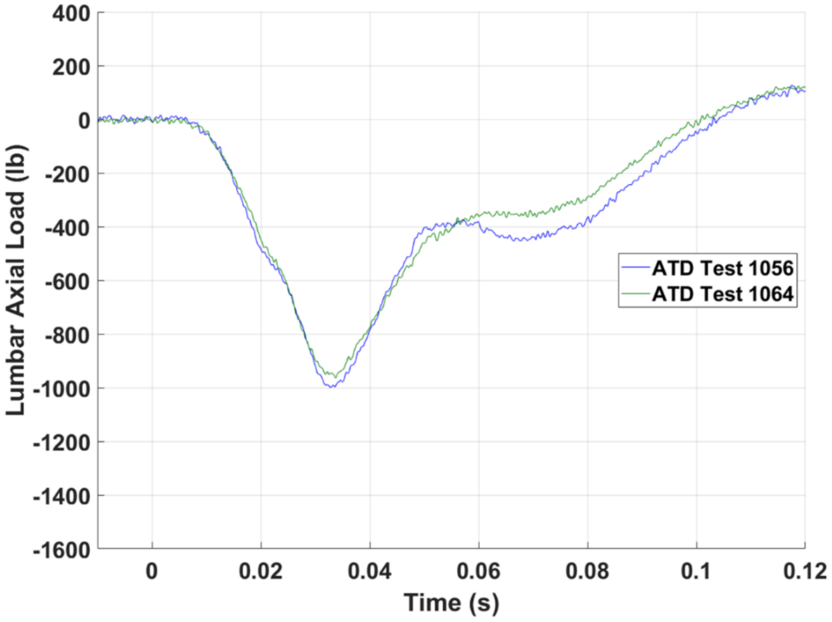

Figure 11. The lumbar axial force versus time data recorded for the matched-pair runs at the Exposure 2 acceleration level for the HIII-5F (ATD Tests 1056 and 1064) are shown. The positive axial load values represent lumbar tension and negative values represent lumbar compression.

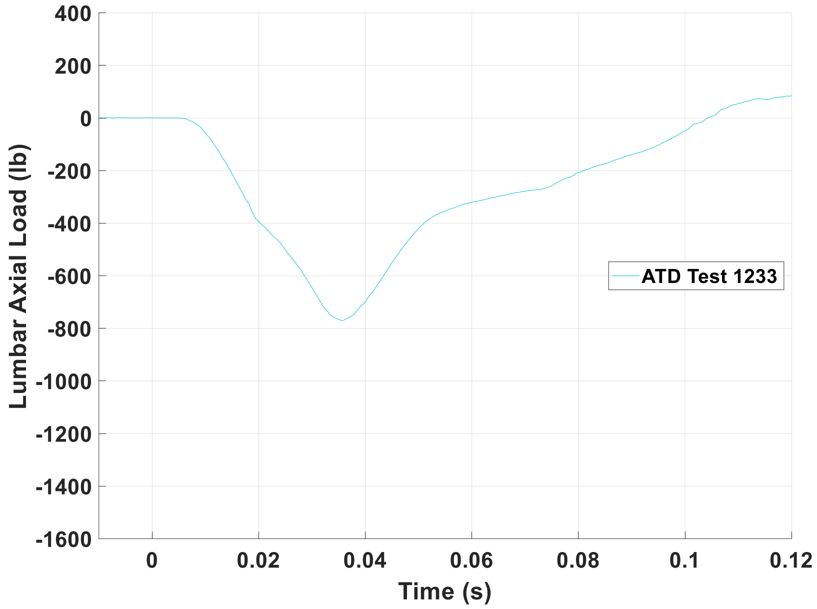

Figure 12. The lumbar axial force versus time data recorded for the matched-pair run at Exposure 3 for the HIII-5F (ATD Test 1233) is shown. The positive axial load values represent lumbar tension and negative values represent lumbar compression.

Table 6. Peak Axial Compressive Lumbar Loads for the HIII-5F Used for Survival Analysis

Female PMHS Testing			**Matched HIII-5F**
Exposure	**PMHS ID**	**Highest AIS**	**Lumbar Axial Compressive Load (lb) ***
1	1	3	1403
2	2	4	999
	3	3	963
3	4	No thoracolumbar injuries	770

*Lumbar axial compressive load is negative by SAE convention; however, they are shown here as absolute values for survival analysis functionality.

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As stated earlier, the injury data were treated as uncensored and the non-injury data were right censored for the development of the moderate or greater (AIS 2+) thoracolumbar injury assessment risk curves, and the three underlying distributions, log-normal, log-logistic, and Weibull, presented AICs of 43.9, 44.3, and 44.7, respectively. The log-normal distribution had the lowest AIC and was chosen for the IARC (Figure 13). The IARVs were identified at 5, 10, 25, 50, 75, 90, and 95 percent (%) injury risk on the AIS 2+ IARC (Table 7). The NCISs were calculated at those discrete values and were found to be below 0.5 and considered “good” at 10, 25, 50, and 75% injury risk level. The covariates of age and bone mineral density were tested and found to have no statistically significant effect on the survival analysis model. A 10% risk of moderate (or greater) thoracolumbar spinal injury (AIS 2+) was selected, as per Lafferty et al. (2021), to determine the IARV for seat development and injury risk assessment for the 5th percentile female population (Table 7).

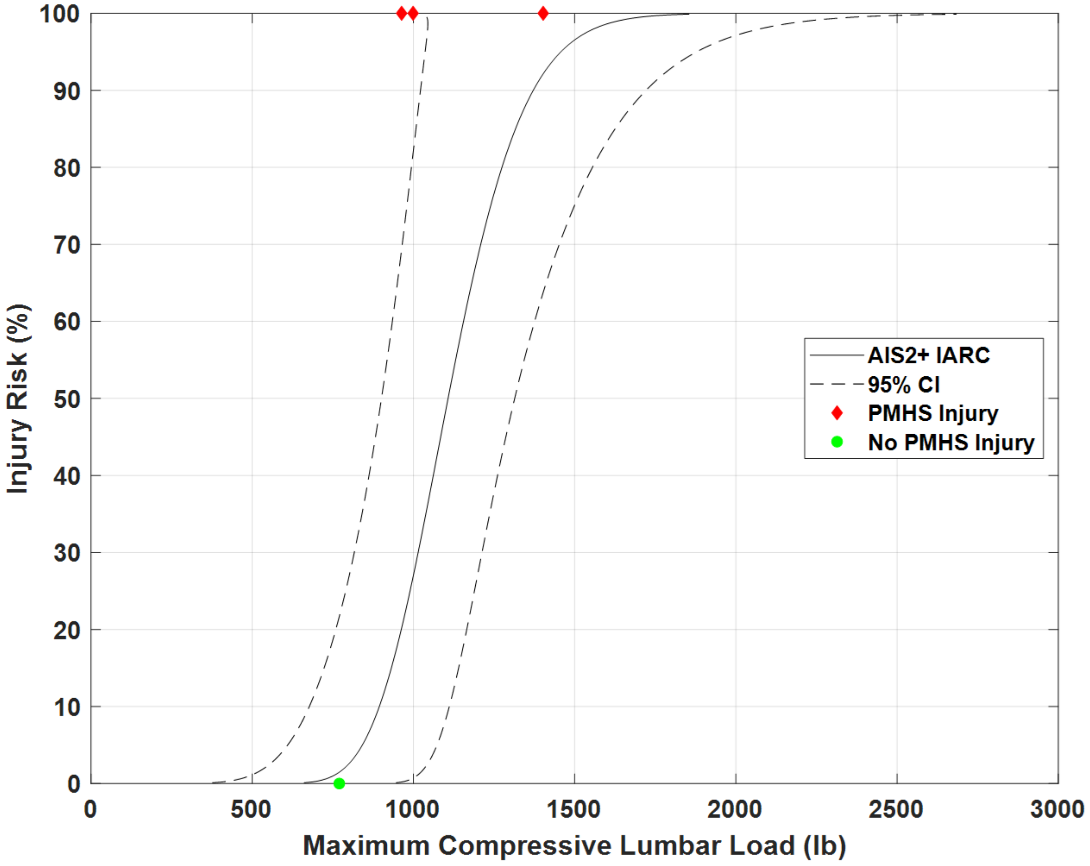

Figure 13. The IARC and associated 95% CIs for the maximum vertical compressive lumbar loads of the HIII-5F for AIS 2+ thoracolumbar injury risk. The ATD peak compressive lumbar load values are plotted (◊/O) against the PMHS AIS 2+ outcome (0% for no AIS 2+ injury and 100% for AIS 2+ injury). (Lumbar axial compressive load is negative by SAE convention; however, they are plotted here as absolute values for survival analysis functionality.)
Note. CI = confidence interval

Table 7. Compressive Lumbar Load AIS 2+ IARVs for the HIII-5F

AIS 2+ Injury Risk (%)	Compressive Load (lb)	NCIS
5	842	0.55
10	**894**	**0.49**
20	962	0.42
25	990	0.40
50	1107	0.37
75	1239	0.42
90	1372	0.51
95	1457	0.58

Note. A 10% risk of AIS 2+ thoracolumbar injury was selected (indicated by the bolded and boxed row). Lumbar axial compressive load is negative by SAE convention; however, they are listed here as absolute values for survival analysis functionality. *Note.* NCIS values of 0.5 were considered “good” (Petitjean et al., 2015).

Discussion

There is a need within the military crashworthiness community to provide female occupant protection recommendations to seat designers and program managers in rotary-wing mishaps. The developed female IARVs were lower than the male IARVs (Table 8), indicating that the female aviator population is more vulnerable to spinal fracture in vertical rotary-wing impact events. However, military seat specifications do not require biomechanical response measurements in the test surrogate (DoD, 1986). Military specifications should be revised or updated including ATD performance requirements to properly assess injury risk for all Soldier populations.

Table 8. USAARL Recommended Lumbar Compressive IARVs for the Female and Male Populations

Soldier Percentile / Sex	ATD	Recommended Lumbar Compressive IARV
5th Female	HIII-5F	894 lb
50th Male	HIII-50M	1135 lb
50th Male	FAA-HIII-50M	1223 lb
95th Male	HIII-95M-PED	1167 lb

There is compelling evidence that the current MIL-S-58095A standard does not appropriately protect the occupant from spinal injury during a survivable crash. For all exposures, the energy level was held constant at 42 ft/s. Three of the four female specimens experienced thoracolumbar injuries. The first PMHS was subjected to peak accelerations that approached but did not exceed the 23 G limit of MIL-S-58095A. This vertical acceleration exposure resulted in a lumbar burst fracture to the specimen. The peak acceleration of Exposure 2 was then lowered from Exposure 1 by 28% to reduce the severity of PMHS injury; however, PMHS 2 and PMHS 3 still experienced lumbar burst fractures. No thoracolumbar injuries were observed in PMHS 4, which had the highest bone mineral density and was exposed to the lowest acceleration pulse.

Two of the four PMHS matched the 5th percentile female Soldier in stature and weight as reported by the 2012 Anthropometric Survey of U.S. Army Personnel: Methods and Summary Statistics (ANSUR II) (Gordon et al., 2014). The 5th percentile female Soldier is approximately 60 inches in stature and weighs 113 lb (Gordon et al., 2014). PMHS 1 and 2 were both 60 inches in stature and 100 lb and 109 lb in weight, respectively. Although PMHS 3 and 4 were outside the 5th percentile range, the data were still used for analysis. As in all PMHS testing, there is a limited availability of specimens, and this is especially true for female specimens. Additionally, the ages of available specimens have historically been biased toward the elderly population. Due to the limited specimen offerings, researchers were compelled to accept specimens that exceeded the anthropometric parameters of the 5th percentile female. The bone mineral density of three of the four PMHS did indicate osteoporosis, therefore, bone mineral density and age were analyzed as covariates, but both were found to not statistically influence the survival analysis results of these four specimens. In a prior study of 43 specimens by Yoganandan et al. (2019), bone mineral density was analyzed as a covariate and resulted in a 32% increase in compressive load at the 10% risk of injury. Although the recommended IARV was developed from older specimens, this is accepted practice within the biomechanics community and typically results in conservative injury thresholds. Furthermore, Brozoski et al. (2020) reported that Army aviators are still at risk for thoracolumbar injuries in potentially survivable mishaps despite the energy mitigation seat specification requirement of MIL-S-58095A. The acceptance of conservative IARVs helps to ensure injury mitigation is provided even when operational impact exposures exceed those conditions applied during the research. However, more specimens should be tested to confirm these findings and to strengthen the analysis and confidence intervals. Additional testing will also inform on and protect a larger percentage of the female aviator population.

Lafferty et al. (2021) used two approaches to develop the interim IARV. First, a basic mass scaling approach was applied, which resulted in a lumbar compressive load IARV of 760 lb. A second experimental approach consisted of performing matched tests with the HIII-5F ATD against the prior male PMHS tests which resulted in a lumbar compressive load IARV of 909 lb. The second experimental/computational approach was within 2% of the IARV developed through matched-pair testing completed with female specimens. The current study offers confidence in the scaling technique conducted by Lafferty et al. (2021), especially when PMHS are difficult to acquire. However, the more conservative female IARV reported in the current study should replace the interim scaled IARVs developed for the HIII-5F ATD lumbar load cell from the legacy male PMHS data.

These IARC and IARV results are only applicable to the HIII-5F design used in this study. Other ATDs may employ different pelvis and lumbar designs which may influence the ATD biofidelity and alter the reactionary forces measured by the lumbar load cell. Thus, the resulting IARC and IARV should not be applied to other ATD designs of similar percentile, such as the Test Device for Human Occupant Restraint 5F (THOR-5F), or other pelvis configurations unless further testing justifies such application. The lumbar compressive IARV recommended in this report is specific to the HIII-5F exposed to the vertical accelerations in the methods.

The IARC was developed using the peak axial compressive lumbar force as uncensored data in accordance with the methodology previously used (Lafferty et al., 2020; Lafferty et al., 2021). Further, uncensored data were determined to be most suitable for this study because the documented PMHS injury severities observed during post-test autopsy were a direct result of the entire exposure, eliminating the need for time of fracture. Censoring the data points associated with injury in any other fashion (left or interval censored) would force assumptions to be made about injury initiation and severity progression that cannot be confirmed. Furthermore, peak load has been commonly used as an injury prediction metric in previous research (Nightingale et al., 1996; Ochia et al., 2003; Arun et al., 2014; Stemper et al., 2015; Stemper et al., 2018) and has been used as uncensored data points for survival analysis (DeVogel et al., 2019). Future work should be considered to improve IARC development and leverage covariates like bone mineral density, age, weight, and interval censoring.

Future military rotary-wing aircraft and crashworthy seat development efforts should include injury assessment for Soldier populations. Military specifications need to update or revise seat performance requirements to require the seat designers and program managers to better protect the seated occupant. Occupant protection recommendations made by the current study provide guidance to improve occupant protection for 5th percentile females during high vertical accelerative loadings. Table 6 provides Army program managers with a choice in how much thoracolumbar injury risk they are willing to accept. However, in the interest of providing a single pass/fail IARV limit, the authors suggest the use of IARVs assuming a 10% risk of an AIS 2 or greater injury (AIS 2+). An occupant that sustains an AIS 2 or greater spinal injury classification would receive more severe spinal injuries with potential for cord involvement and instability. These spinal injuries would likely degrade a Soldier’s ability to self-egress or perform critical duties. AIS 2 type injuries still include any number of vertebral body fractures and minor injury to the spinal cord. In fact, an individual with a series of adjacent level vertebral body factures would have a very unstable spinal column; however, this set of injuries would only be coded as having AIS 2 level injuries. As such, the authors suggest only allowing for a low, 10% risk, of AIS 2 or greater injury (Lafferty et al., 2020). These metrics are only reflective of spinal injury and do not control for other chest injuries, like rib fractures.

Conclusions

Military specifications should be updated or revised to include ATD-based performance requirements to properly assess injury risk for all Soldier populations. The IARVs for the lumbar load cell of the HIII-5F presented in this report will guide the assessment of injury risk for the seated 5th percentile female Soldier in vertical accelerative loadings during helicopter mishaps.

The IARCs were developed using the lumbar load cell in the HIII-5F to assess vertebral body fractures categorized as AIS 2+ injuries. To mitigate the risk of a vertebral fracture in an impact event, a 10% risk was chosen on the IARC to determine the IARV. It is recommended that vertical compressive lumbar loads should not exceed 894 lb when testing with an HIII-5F ATD to control for a 10% risk of AIS 2 or greater injury. The IARV reported in this study should replace the interim scaled IARVs developed by Lafferty et al. (2021).

Recommendations

a. Instrumented ATDs, for the purpose of injury assessment, should be required for future military rotary-wing aircraft and crashworthy seat development efforts. The ATD chosen should be consistent with the anthropometry of the population being tested and should have militarily relevant injury assessment capabilities.

b. A 10% risk of moderate or higher severity thoracolumbar spinal injury (AIS 2+) is recommended to determine the IARV to assess seat crashworthiness and injury risk assessment for the 5th percentile female Soldier.

c. The female IARV reported in the current study should replace the interim scaled IARVs developed for the Hybrid III 5th percentile female ATD lumbar load cell from the legacy male PMHS data.

d. When an HIII-5F ATD is exposed to dynamic vertical loading conditions in an upright seated posture, an axial compressive lumbar load performance limit of 894 lb is the IARV recommended for a 10% risk of moderate and more severe thoracolumbar spinal injury (AIS 2+).

e. Further work that includes additional female PMHS to update or validate the IARCs is needed.

This report is one of three USAARL technical reports that developed thoracolumbar IARVs for the 5th female, 50th, and 95th percentile male ATDs. In addition to the specific recommendations listed above, it is recommended that a general summary report be written for rotary-wing crashworthy seat vertical performance requirements.

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